F-15 837 IFCS
Intelligent Flight Control System Project

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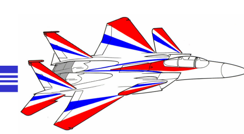
NASA, Dryden Flight Research Center

Project Participants

- **Nasa Dryden Flight Research Center**
  - Responsible test organization for the flight experiment
    - Flight, range and ground safety
    - Mission success
- **Nasa Ames Research Center**
  - Development of the concepts
- **Boeing STL Phantom Works**
  - Primary flight control system software (Conventional mode)
  - Research flight control system software (Enhanced mode)
- **Institute for Scientific Research**
  - Neural Network adaptive software
- **Academia**
  - West Virginia University
  - Georgia Tech
  - Texas A&M

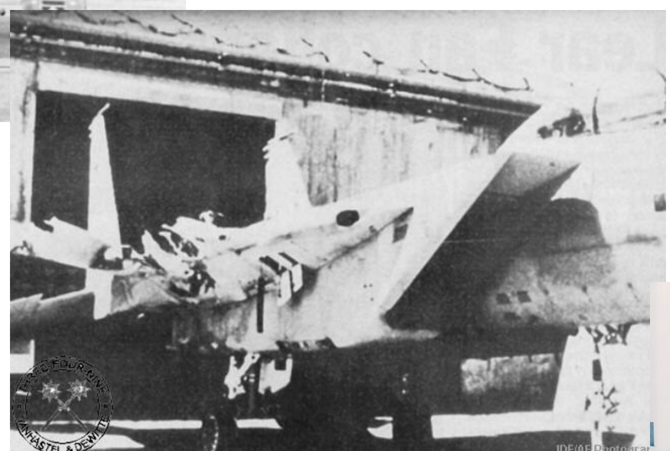


F-15 IFCS Project Goals

- **Demonstrate Revolutionary Control Approaches that can Efficiently Optimize Aircraft Performance in both Normal and Failure Conditions**

- **Advance Neural Network-Based Flight Control Technology for New Aerospace Systems Designs**

Motivation

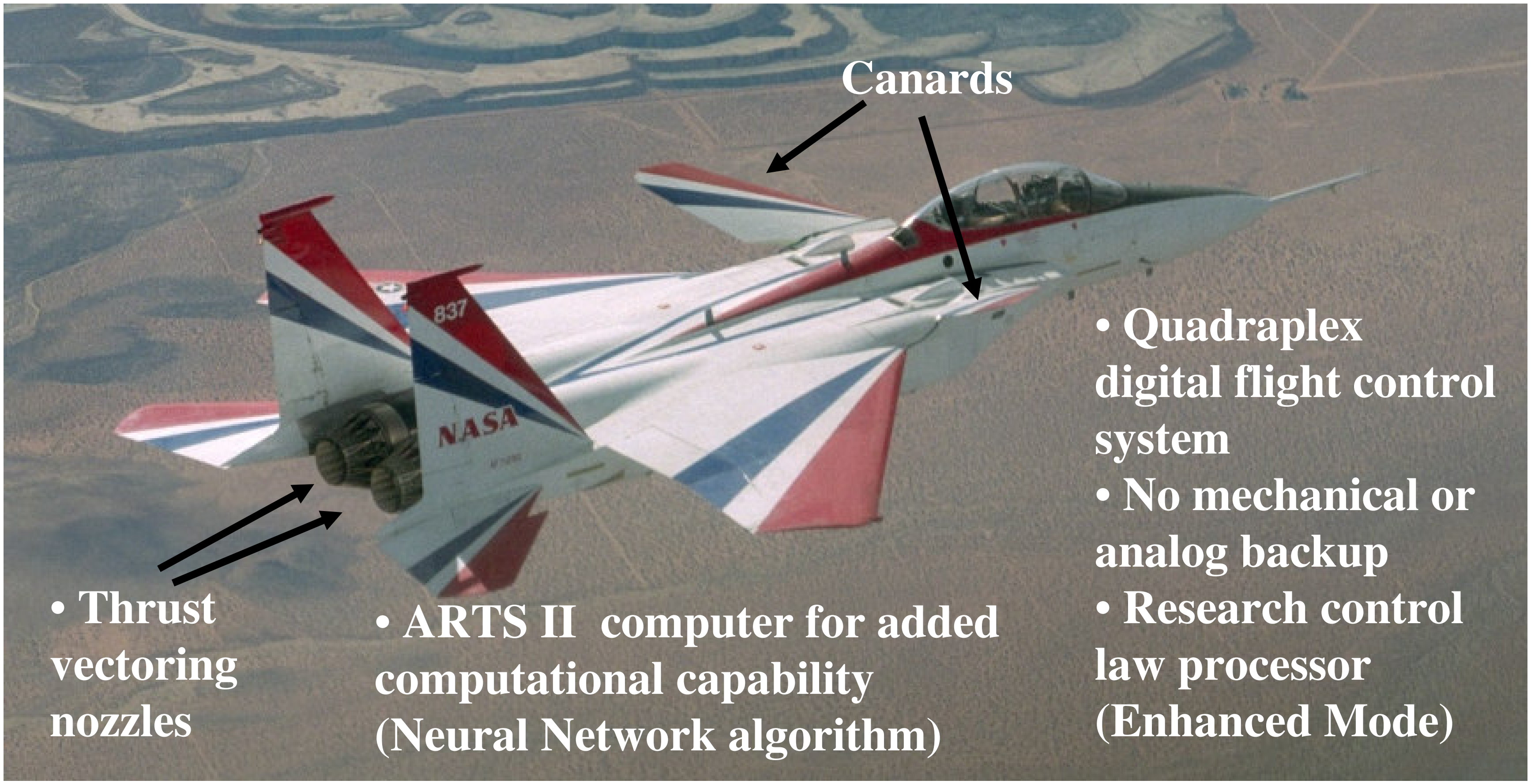


These are survivable accidents

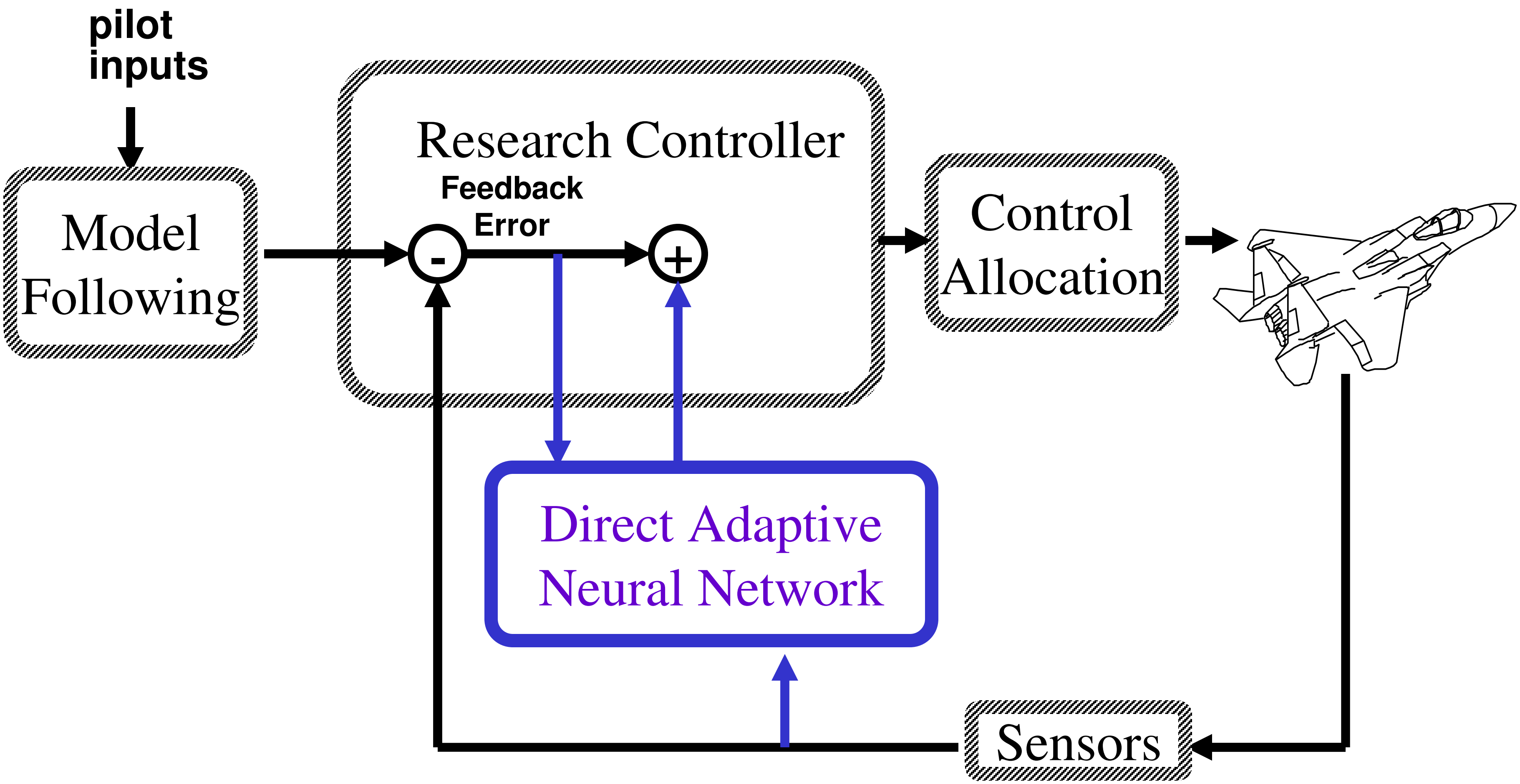
IFCS has potential to reduce the amount of skill and luck required for survival

NASA NF-15B Tail Number 837

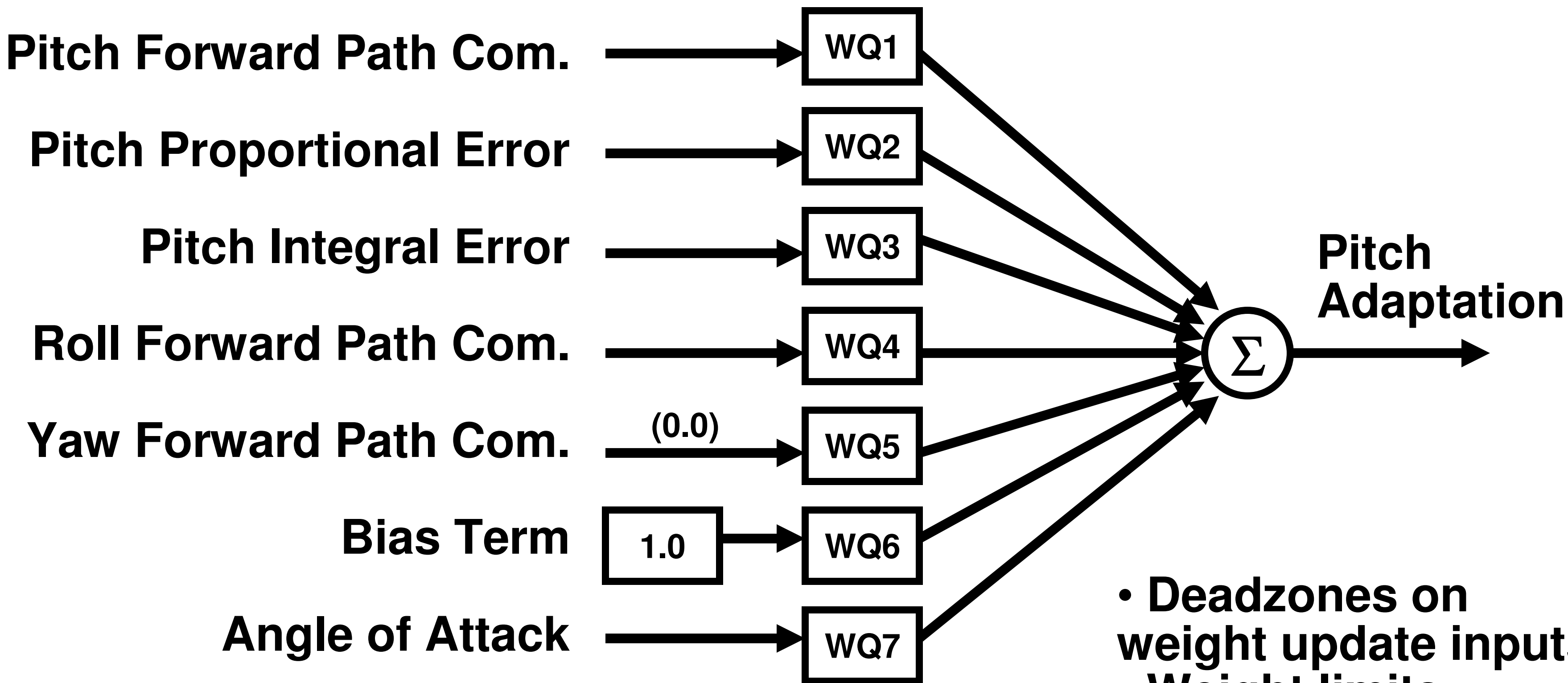
Extensively modified F-15 airframe



Gen II Direct Adaptive Control Architecture
(Adaptive)



Simplified Sigma-Pi Neural Network
Pitch Axis

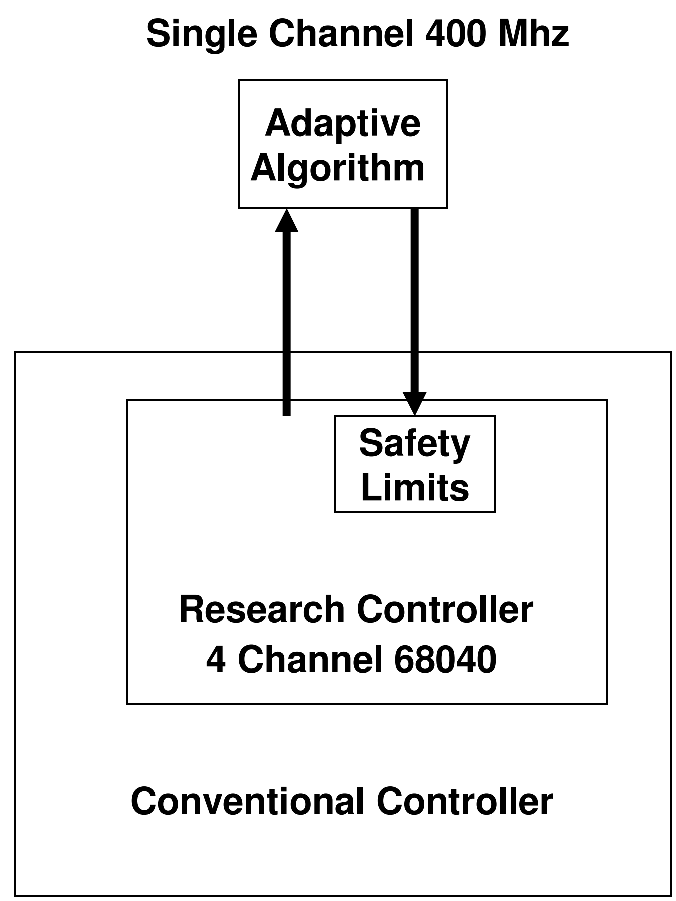


- Deadzones on weight update inputs
- Weight limits

Weight Update Law: $\dot{W} = -G(U_{err} B_a + L U_{err} W)dt$

Limited Authority System

- Adaptation algorithm implemented in separate processor
  - Class B software
  - Autocoded directly from Simulink block diagram
  - Many configurable settings
    - Learning rates
    - Weight limits
    - Thresholds, etc.
- Control laws programmed in Class A, quad-redundant system
- Protection provided by floating limiter on adaptation signals

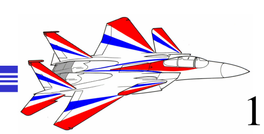


Flight Experiment

- **Assess handling qualities of Gen II controller without adaptation**
- **Activate adaptation and assess changes in handling qualities**
- **Introduce simulated failures**
  - **Control surface locked ("B matrix failure")**
  - **Angle of attack to canard feedback gain change ("A matrix failure")**
- **Re-assess handling qualities with simulated failures and adaptation.**
- **Report on "Real World" experience with a neural network based flight control system**

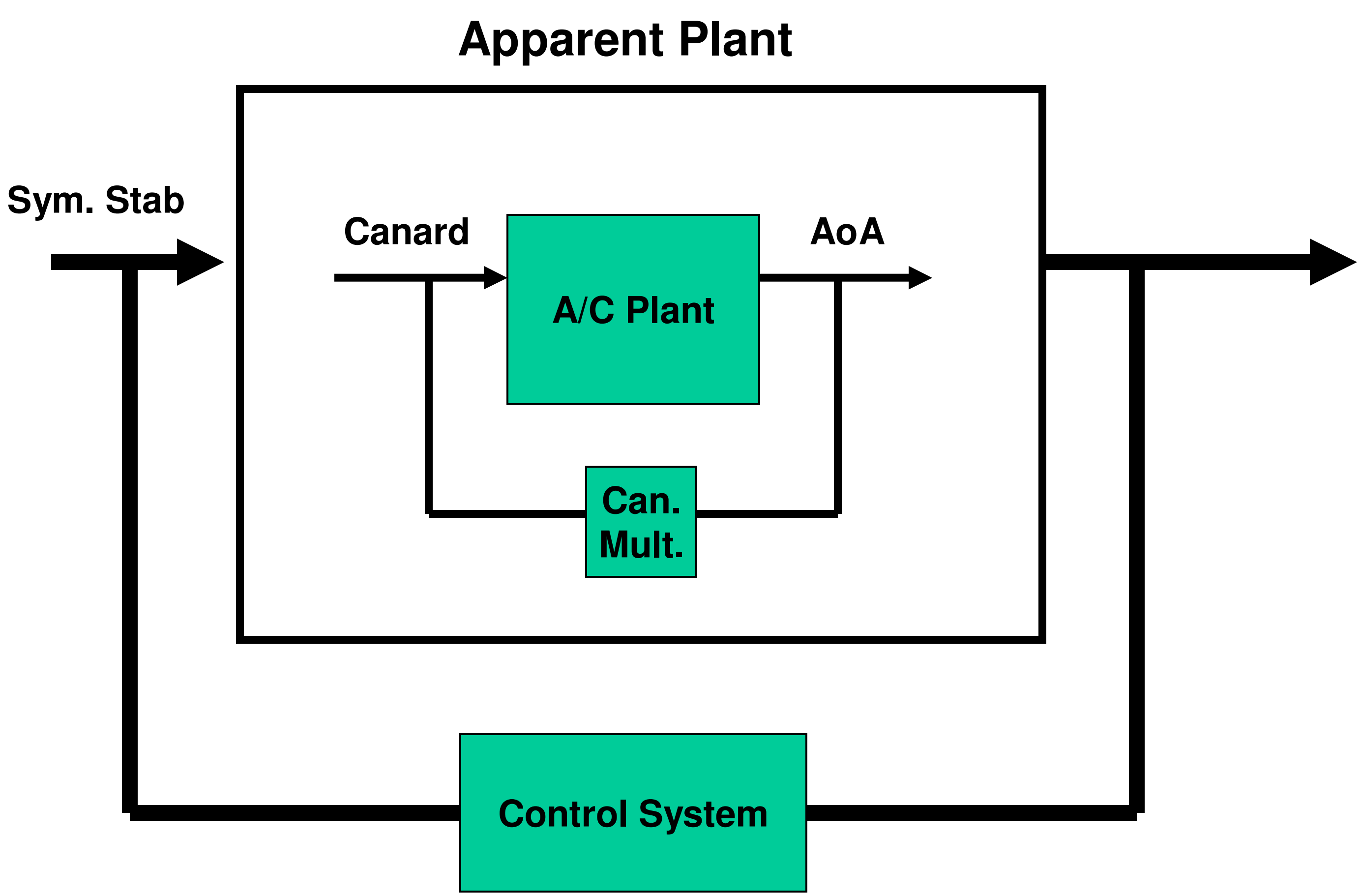
Adaptation Goals

- Ability to suppress initial transient due to failure
  - Trade-off between high learning rate and stability of system
- Ability to re-establish model following performance
- Ability to suppress cross coupling between axes
  - No existing criteria



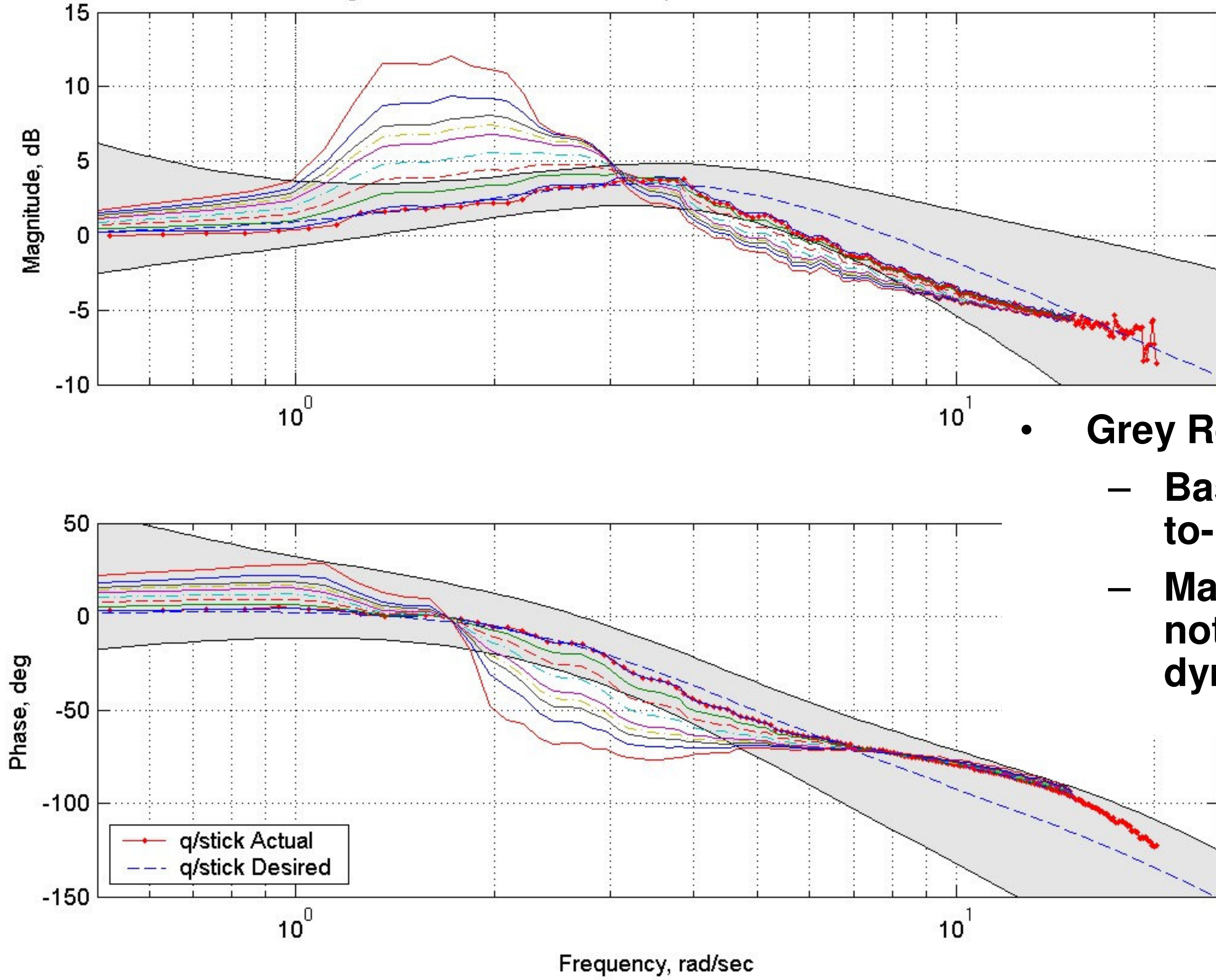
Simulated Destabilization
A-Matrix Failure

Effect of Canard Multiplier



Canard Multiplier Effect
Closed Loop Freq. Resp.

Figure 3 - F-15 IFCS Closed Loop Technical Performance Metric

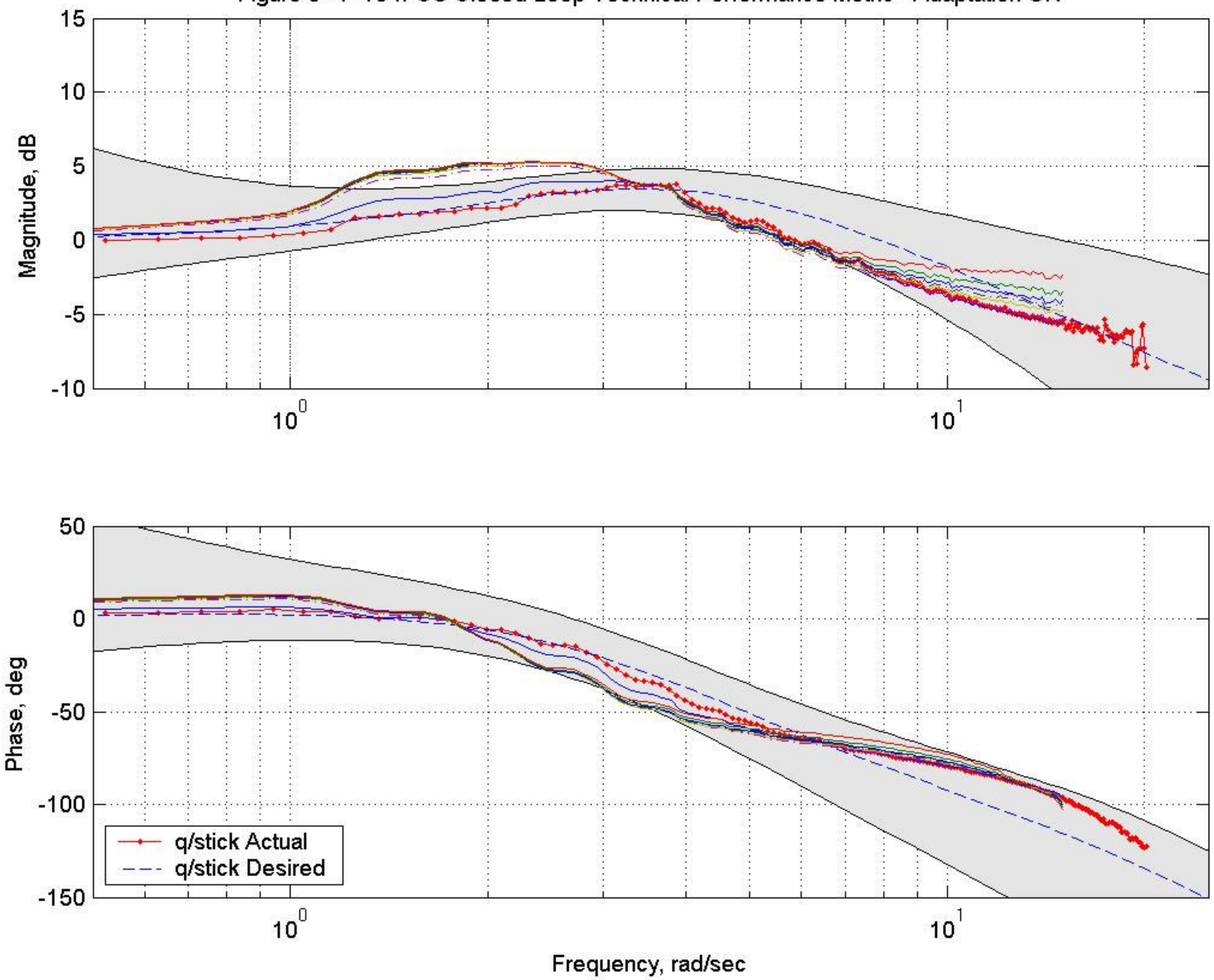


- Grey Region:
  - Based on model-to-be-followed
  - Maximum noticeable dynamics (LOES)

Canard Multiplier Effect

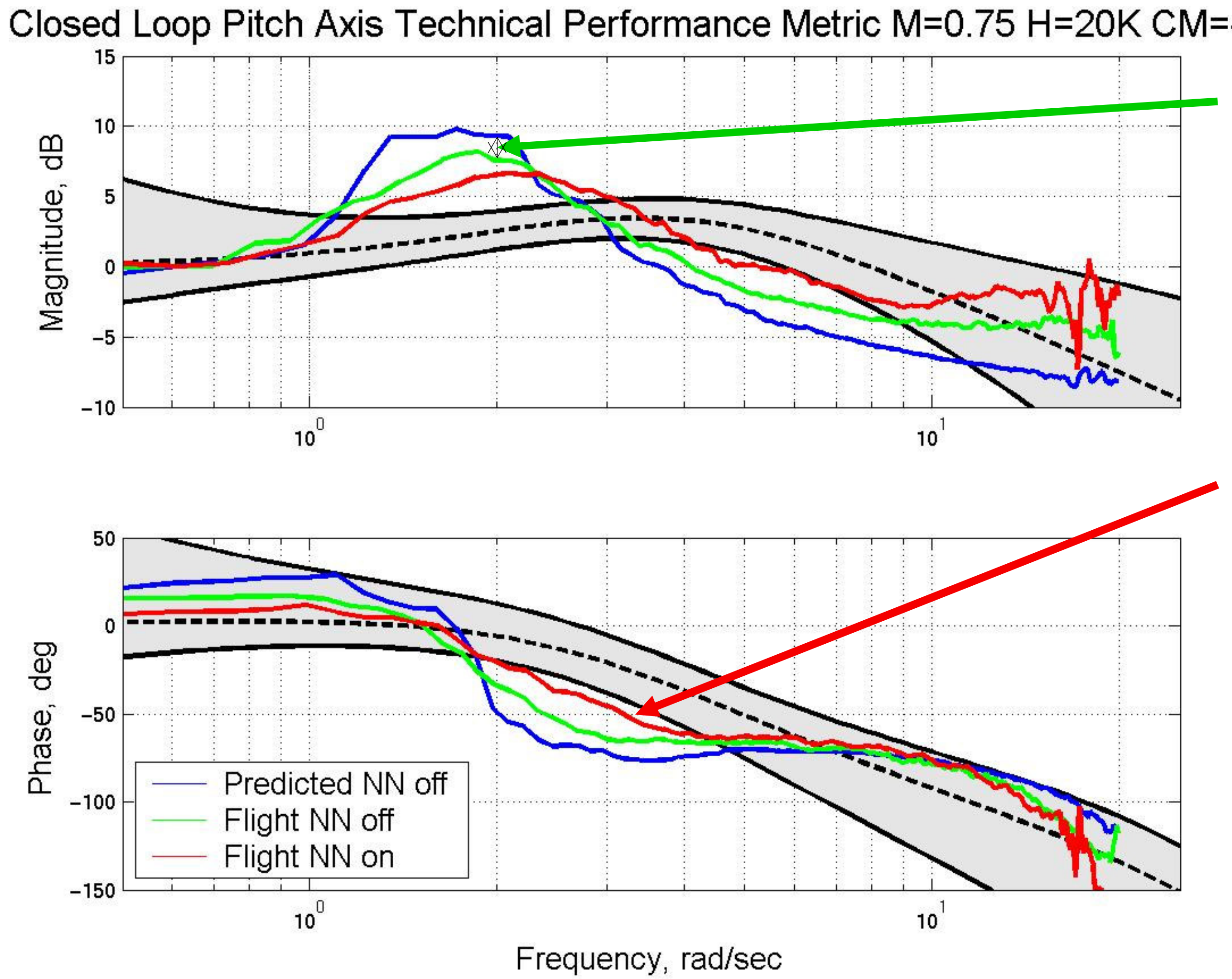
Closed Loop with Adaptation

Figure 5 - F-15 IFCS Closed Loop Technical Performance Metric - Adaptation ON



Simulated Destabilization Failure

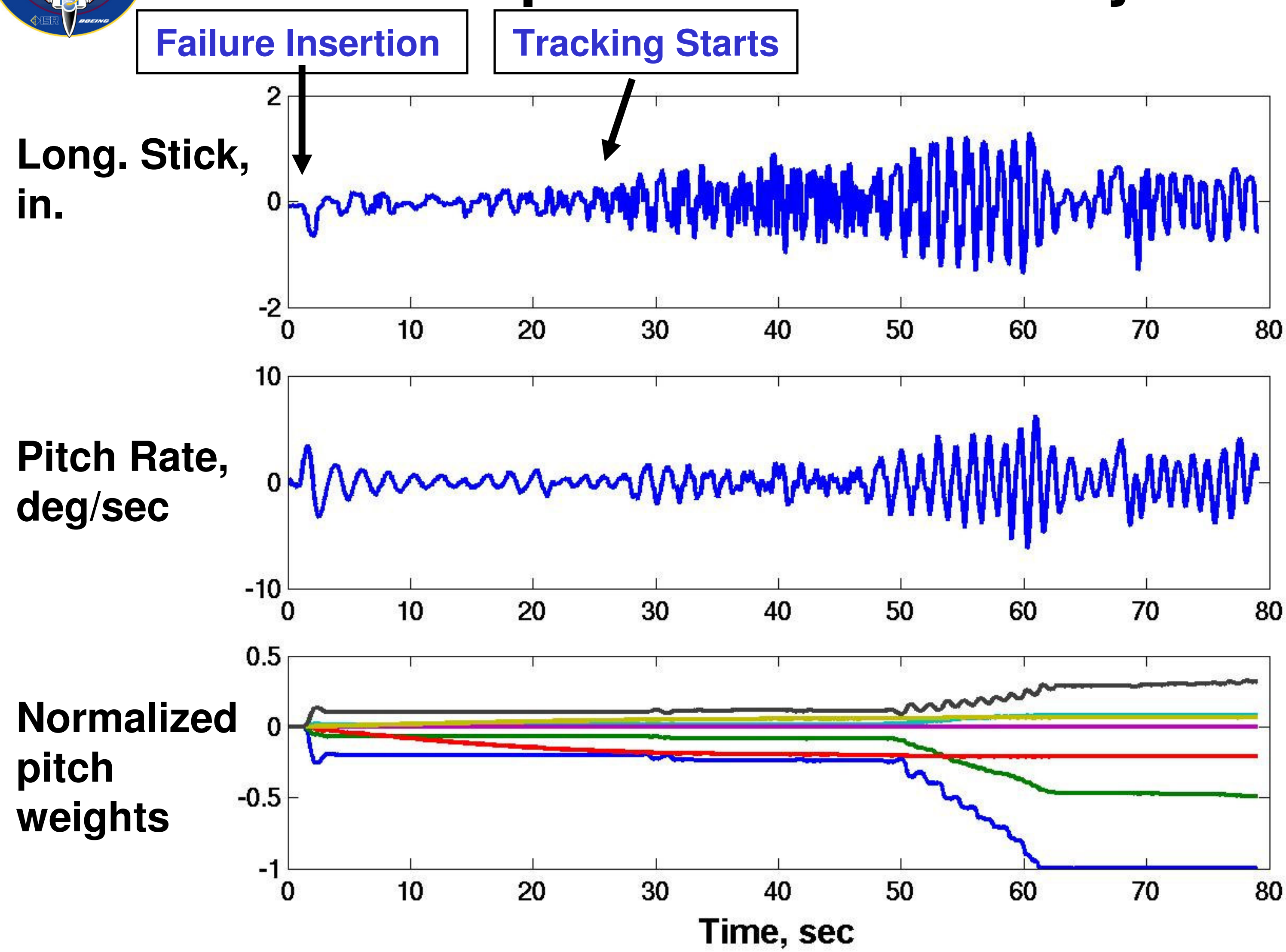
(Angle of Attack Feedback Change)



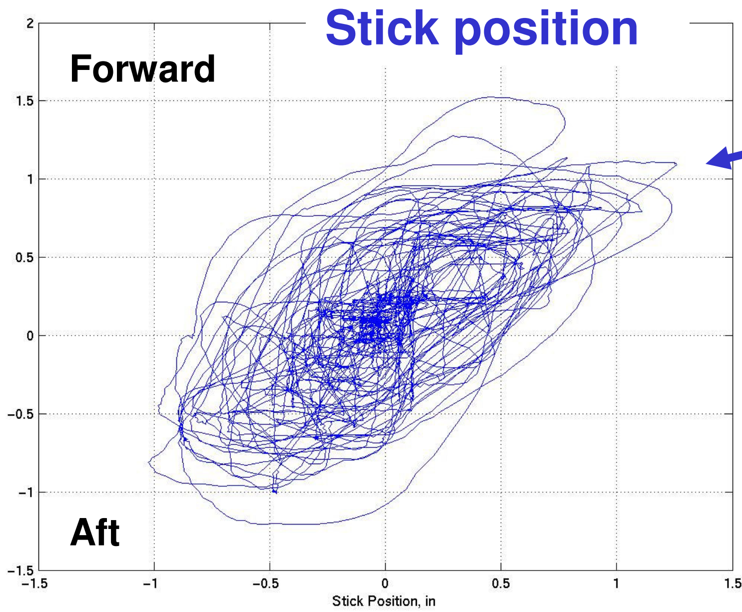
- **Effect of simulated failure less than predicted**
- **Adaptation Improved response**
- **Software change in work to increase failure size**

Simulated Stabilator Failure

Adaptation Time History

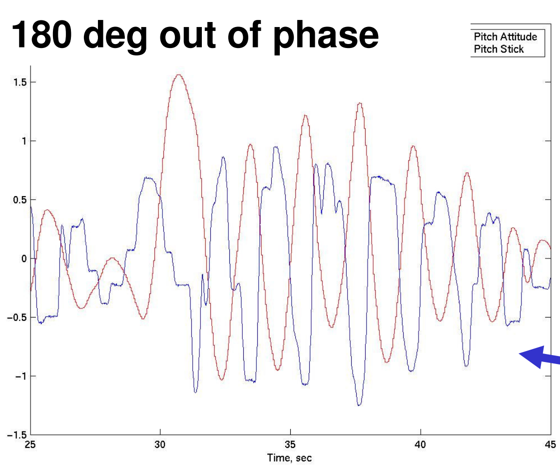


Simulated Frozen Stabilator



- Pilot unconsciously compensates for asymmetry

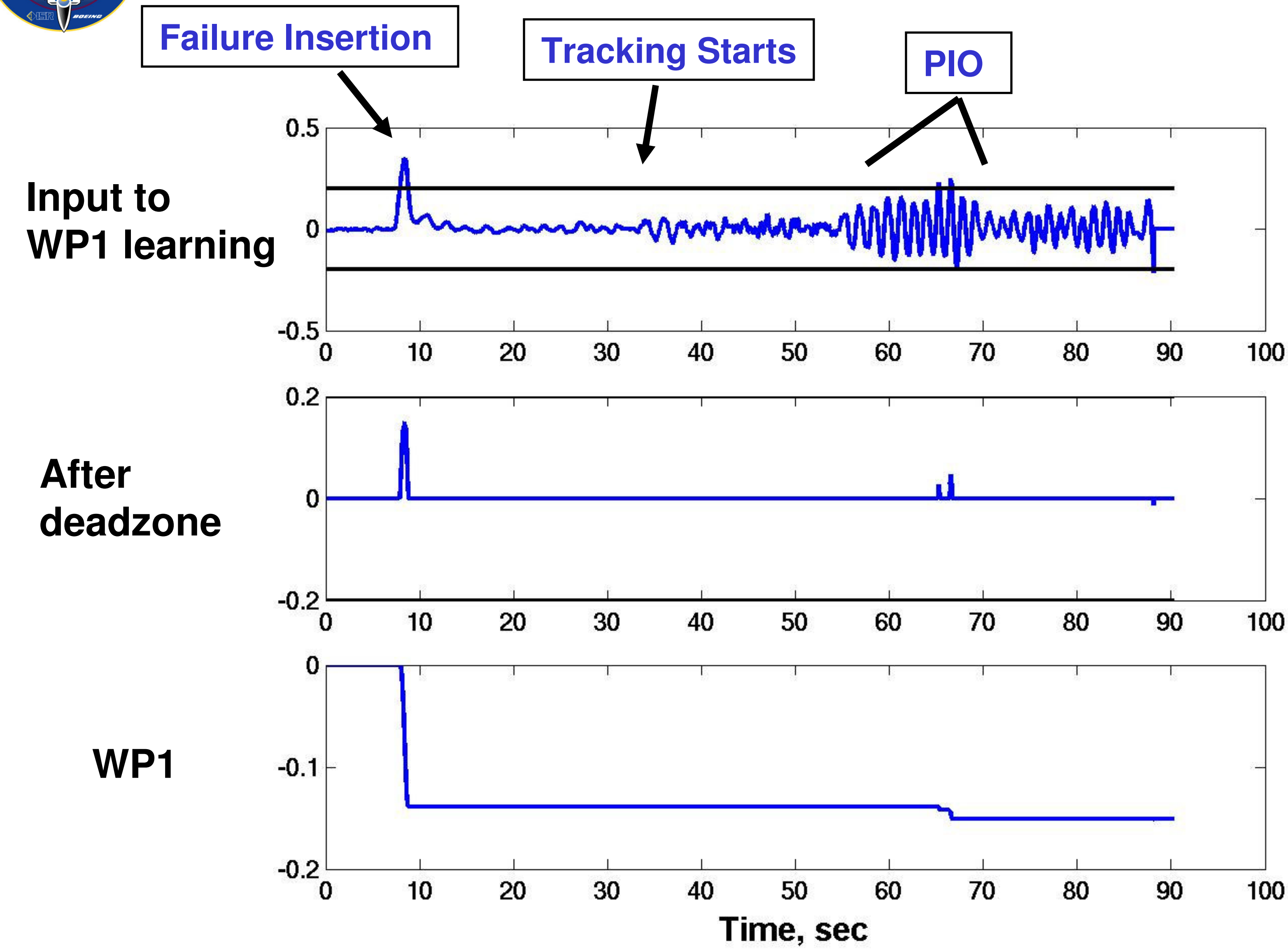
- Correlated pilot input presents greater challenge for adaptive system



\+ Adaptive system reduced the amount of cross coupling

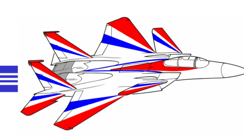
\- Adaptive system also introduced tendency for pilot induced oscillations (PIO)

Deadzone Effect



Direct Adaptive
Experience and Lessons Learned

- Initial simulation model had high bandwidth
  - Majority of system performance achieved by the dynamic inversion controller
  - Direct adaptive NN played minor role
- Dynamic Inversion gains reduced to meet ASE attenuation requirements
  - Much harder to achieve desired performance
  - NN contribution increased
- Initial performance objective emphasized transient reduction and achieving model following after failure
  - Piloted simulation results showed that reducing cross coupling was more important objective
- Explicit cross terms in NN required for failure cases
  - Relying on disturbance rejection alone doesn’t work (also finding of Gen 1)



Direct Adaptive
Experience and Lessons Learned

- Liapunov proof of bounded stability
  - Necessary but not sufficient proof of stability
  - Many cases of limit cycle behavior observed
  - Other analytic methods required for ensuring global stability
- Dynamic Inversion controller contributes significantly to cross coupled response in presence of surface failure (locked)
  - Redesigned yaw loop using classical techniques
- NN’s require careful selection of inputs
  - Presence of transient errors “normal” for abrupt inputs in non-adaptive systems
  - Existence of transient errors tend to drive NN’s to “high gain” trying to achieve impossible
- Significant amount of “tuning” required for to achieve robust full envelope performance
  - Contradicts claim of robustness to unforeseen failures
  - Piloted nonlinear simulation required

Conclusions

- Adaptive system generally behaved as predicted
  - Weights adjusted in correct direction
  - Real world turbulence and measurement noise did not adversely affect learning
  - Only safety disengagements observed were due to very aggressive pilot inputs
- Simulated destabilization less than predicted
  - Flight vehicle more stable than aero model predicts
  - Software change in work to increase destabilizing gain
- No metrics currently exist for damaged vehicles

- Gained valuable real world experience that has already pushed technology to more acceptable level

Potential Future Work

- How to sense and incorporate structural limitations into the adaptive algorithm
- Develop better metrics – What is most important to ensure that a damaged vehicle can be safely landed?
- Further investigation of asymmetric failure
  - Determine source of PIO and develop means to suppress it
  - Does stab failure require more complicated (nonlinear) neural network or direct adaptation of control surface mixer?
- Investigate adaptive notch filters to avoid adverse aero-servo-elastic (ASE) interactions

- Maintain long-term effort to advance adaptive control technology